SLAC-PUB-8738
BABAR-PROC-00/24
November, 2000

First Measurement of the *CP*-Violating Asymmetries with *BABAR*

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Abstract

We report on a preliminary measurement of time-dependent *CP*-violating asymmetries in $B^0 \rightarrow J/\psi K^0_S$ and $B^0 \rightarrow \psi(2S)K^0_S$ decays recorded by the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. The data sample consisted of $9.0\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance and $0.8\,\mathrm{fb}^{-1}$ off-resonance. One of the pair of neutral B mesons produced at the $\Upsilon(4S)$ was fully reconstructed, while the flavor of the other neutral B meson was tagged at the time of its decay. The value of the asymmetry amplitude, $\sin 2\beta$, was determined from a maximum likelihood fit to the time distribution of 120 tagged candidates to be $\sin 2\beta = 0.12 \pm 0.37(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$ (preliminary).

Contributed to the Proceedings of the DPF2000 Meeting
of the Division of Particles and Fields of the American Physics Society,
8/9/2000—8/12/2000, Columbus, OH

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Work supported in part by Department of Energy contract DE-AC03-76SF00515.

The *CP*-violating phase of the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix can provide an elegant explanation of the *CP*-violating effects seen in decays of neutral K mesons[1]. The unitarity relations between the elements of the CKM matrix can be expressed as six triangles of equal area in the complex plane. A nonzero area[2] directly implies the existence of a *CP*-violating CKM phase. The most experimentally accessible of the unitarity relations involves elements V_{ub} and V_{td}, and is known as the Unitarity Triangle, where angles, and hence size of *CP*-violating asymmetries are expected to be large[3]. Observing the *CP*-violating asymmetry can thus provide a crucial test of the Standard Model.

The *CP*-violating asymmetry in $b \to c\bar{c}s$ decays of the B^0 meson such as $B^0/\overline{B}^0 \to J/\psi K^0_S$ (or $B^0/\overline{B}^0 \to \psi(2S) K^0_S$) is caused by the interference between mixed and unmixed decay amplitudes. With little theoretical uncertainty, the phase difference between these amplitudes is equal to twice the angle β of the Unitarity Triangle. In e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance a $B^0\overline{B}^0$ pair produced in $\Upsilon(4S)$ decay evolves in a coherent P-wave until one of the B mesons decays. For this measurement, one of the B mesons (B_{CP}) is fully reconstructed in a *CP* eigenstate ($J/\psi K^0_S$ or $\psi(2S)K^0_S$). If the other B meson (B_{tag}) is determined to decay to a state of known flavor at a certain time t_{tag}, B_{CP} is *at that time* known to be of the opposite flavor. By measuring the proper time interval $\Delta t = t_{CP} - t_{tag}$ from the B_{tag} decay time to the decay of the B_{CP}, it is possible to determine the time evolution of the initially pure B^0 or $\overline{B}^0$ state. The experimental time-dependent decay rate into the B_{CP} final state is given by

$$\mathcal{F}_{\pm} = \frac{1}{4}\,\Gamma\,\mathrm{e}^{-\Gamma|\Delta t|}\,\left[\,1\,\pm\,\mathcal{D}\sin 2\beta \times \sin\Delta m_d\,\Delta t\,\right]\,\otimes\mathcal{R}(\,\Delta t\,;\,\hat{a}\,)\;, \tag{1}$$

where the $+$ or $-$ sign indicates whether the B_{tag} is tagged as a B^0 or a $\overline{B}^0$, respectively. The “dilution factor” $\mathcal{D}$ is given by $\mathcal{D} = 1 - 2w$, where w is the mistag fraction, *i.e.*, the probability that the flavor of the tagging B is identified incorrectly. The term $\mathcal{R}$ accounts for the finite detector resolution, where $\hat{a}$ represents the set of parameters that describe the resolution function.

1 Sample Selection

For this analysis we used a sample of $9.8\,\mathrm{fb}^{-1}$ of data recorded by the *BABAR* detector [6] between January 2000 and the beginning of July 2000, of which $0.8\,\mathrm{fb}^{-1}$ was recorded $40\,\mathrm{MeV}$ below the $\Upsilon(4S)$ resonance (off-resonance data). At PEP-II, B mesons are produced in the asymmetric collisions of 9 GeV electrons and 3.1 GeV positrons, and have an average boost along z direction of $\langle\beta\gamma\rangle = 0.56$.

J/ψ candidates were identified through their decays into e^+e^- and $\mu^+\mu^-$, and $\psi(2S)$ candidates were reconstructed in e^+e^-, $\mu^+\mu^-$, and $J/\psi\,\pi^+\pi^-$ modes[7]. In the electron modes of J/ψ and $\psi(2S)$, at least one electron was required to be positively identified. An algorithm for the recovery of Bremsstrahlung photons[7] was used if both electrons were positively identified. Similarly, for the $\mu^+\mu^-$ candidates, at least one muon was required to pass particle identification criteria. The charmonium states then were selected in a window around their expected mass[7], and were combined with K^0_S candidates reconstructed through their decays into $\pi^+\pi^-$ and $\pi^0\pi^0$ states[7] to form B_{CP} candidates. B_{CP} candidates were identified with a pair of nearly uncorrelated kinematic variables: the difference ΔE between the energy of the B_{CP} candidate and the beam energy in the center-of-mass frame, and the beam-energy substituted mass m_{SE} [6]. The signal region was defined by $5.270\,\mathrm{GeV}/c^2 < m_{\mathrm{SE}} < 5.290\,\mathrm{GeV}/c^2$ and an approximately three-standard-deviation cut on ΔE (typically $|\Delta E| < 35\,\mathrm{MeV}$). The *CP* sample used in this analysis was composed of 168

candidates: 121 in the $J/\psi K_S^0$ ($K_S^0 \to \pi^+\pi^-$) channel, 19 in the $J/\psi K_S^0$ ($K_S^0 \to \pi^0\pi^0$) channel and 28 in the $\psi(2S)K_S^0$ ($K_S^0 \to \pi^+\pi^-$) channel.

2 Time Resolution Function

All tracks in the event, excluding those from B_{CP}, were fit to a common vertex using an iterative procedure, which at each step removes a track with the worst χ^2 greater than 6. Information on the direction of the B_{CP}, derived from the kinematics of the reconstructed B_{CP} and the average position of the interaction point, was also used in the fit. In order to reduce bias, all pairs of tracks that can be reconstructed as long-lived neutral particles (V^0s), were replaced by the corresponding V^0 candidates in the fit. Events were rejected if either B_{CP} or B_{tag} does not converge, or if reconstructed Δz or its uncertainty were large($|\Delta z| > 3\,\mathrm{mm}$ or $\sigma_{\Delta z} > 400\,\mu\mathrm{m}$).

The time resolution function is described accurately by the sum of three Gaussian distributions, which has six independent parameters:

$$\mathcal{R}(\,\Delta t;\,\hat{a}\,) \;=\; \sum_{i=1}^{3} \frac{f_i}{\sigma_i\sqrt{2\pi}} \exp\left(-(\Delta t-\delta_i)^2/2{\sigma_i}^2\right) . \tag{2}$$

A fit to the time resolution function in Monte Carlo simulated events indicated that most of the events ($f_1 \approx 1 - f_2 = 70\%$) were in the core Gaussian, which has a width $\sigma_1 \approx 0.6\,\mathrm{ps}$. The wide Gaussian had a width $\sigma_2 \approx 1.8\,\mathrm{ps}$. Tracks from forward-going charm decays included in the reconstruction of the B_{tag} vertex introduced a small bias, $\delta_1 \approx -0.2\,\mathrm{ps}$, for the core Gaussian. The third Gaussian, used to parameterize events at very large values of Δz due to poorly reconstructed vertices, had a fixed width of 8 ps and a fraction $f_w \sim 1\%$[5]. In likelihood fits, the widths of the first and second Gaussian were parameterized by event-by-event error $\sigma_{\Delta t}$ from the vertex fits and two scale factors $\mathcal{S}_1$ and $\mathcal{S}_2$ ($\sigma_1 = \mathcal{S}_1 \times \sigma_{\Delta t}$ and $\sigma_2 = \mathcal{S}_2 \times \sigma_{\Delta t}$). Parameters $\mathcal{S}_2 = 2.1$ and $f_2 = 0.25$ were determined from Monte Carlo, bias of the second Gaussian δ_2 was fixed at 0 ps, and three remaining parameters $\hat{a} = \{\mathcal{S}_1, \delta_1, f_w\}$ were determined from the observed vertex distributions in the hadronic B^0 decays. The time resolution is dominated by the precision of the B_{tag} vertex position, and we found no significant differences in the Monte Carlo simulation of the resolution function parameters for the various fully reconstructed decay modes[5].

3 *B* flavor tagging

Each event with a *CP* candidate was assigned a B^0 or $\overline{B}^0$ tag if the rest of the event (*i.e.,* with the daughter tracks of the B_{CP} removed) satisfies the criteria for one of several tagging categories. Three tagging categories relied on the presence of a fast lepton or one or more charged kaons in the event. Two categories, called neural network categories, were based upon the output value of a neural network algorithm applied to events that have not already been assigned to lepton or kaon tagging categories.

The mistag fractions w_i were measured directly for each tagging category by studying the probability of flavor mixing in events in which one B^0 candidate, called the B_{rec}, was fully reconstructed in a flavor eigenstate mode[4]. Both integrated and time-dependent analyses of the fraction of mixed events are sensitive to the to the mistag fraction. In the time-dependent analysis, the probability density functions of unmixed (+) and mixed (−) events were defined similar to Eq. (1)

$$\mathcal{H}_\pm = \frac{1}{4}\,\Gamma\,\mathrm{e}^{-\Gamma|\Delta t|}\,\left[\,1\,\pm\,\mathcal{D}\times\cos\Delta m_d\,\Delta t\,\right]\otimes\mathcal{R}(\,\Delta t;\,\hat{a})\,. \tag{3}$$

These functions were used in an maximum maximum likelihood fit to the large samples of fully reconstructed B^0 decays into hadronic and semileptonic modes to determine mistag fractions $w_i = \frac{1}{2}(1 - \mathcal{D}_i)$ for each tagging category i. We find the tagging efficiency $\varepsilon = (76.7 \pm 0.5)\%$ and the effective tagging efficiency $Q = \varepsilon\ (1 - 2w)^2 = (27.9 \pm 0.5)\%$ (statistical errors only)[4]. Out of 168 *CP* candidates, 120 were tagged: 70 as B^0 and 50 as $\overline{B}^0$.

4 Extracting sin2β

The value of sin2β was determined from an unbinned maximum likelihood fit to the time-dependent distribution of tagged B_{CP} decays[5]. The fitting procedure was extensively tested in "toy" Monte Carlo simulations, where effects backgrounds, different resolution function parameterizations, and behavior of the fit on small statistical samples were studied. We also verified the reconstruction and fitting procedure on a large sample of events produced with the full *BABAR* GEANT3 detector simulation.

The analysis was also validated on the various data control samples where the *CP* asymmetry was expected to be zero. An "apparent *CP* asymmetry" was studied on a sample of $B^+ \to J/\psi K^+$ events and events with self-tagged $B^0 \to J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$) decays. We also use the event samples with fully-reconstructed candidates in charged or neutral hadronic modes. In all cases, the apparent *CP* asymmetry was found to be consistent with zero[5].

We have adopted a blind analysis for the extraction of sin2β in order to eliminate possible experimenter's bias. We used a technique that hides not only the result of the unbinned maximum likelihood fit, but also the visual *CP* asymmetry in the Δt distribution. The error on the asymmetry was not hidden. With these techniques, numerous systematic studies could be performed while keeping the numerical value of sin2β hidden. The analysis procedure for extracting sin2β was frozen, and the data sample fixed, prior to unblinding.

Using the maximum-likelihood fit to the full data sample of $B^0/\overline{B}^0 \to J/\psi K^0_S$ and $B^0/\overline{B}^0 \to \psi(2S)K^0_S$ events, we determined[5]

$$\sin 2\beta = 0.12 \pm 0.37(\text{stat.}) \pm 0.09(\text{syst.})\ (\text{preliminary}). \tag{4}$$

Systematic errors arise from uncertainties in input parameters to the maximum likelihood fit, incomplete knowledge of the time resolution function, uncertainties in the mistag fractions, and possible limitations in the analysis procedure.

5 Conclusions and prospects

We have presented the first measurement of the *CP*-violating asymmetry parameter sin2β in the B meson system by *BABAR*Collaboration. Our measurement is consistent with the presently available data[8], and also agrees within two standard deviations with the value determined by other constraints of the Unitarity Triangle[3]. While the current experimental uncertainty on sin2β is large, the next few years will bring significant improvements in precision. Measurements of *CP*-violating asymmetries in other final states are also underway, and will help constrain the Standard Model description of *CP* violation.

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